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RESEARCH MEMORANDUM

USE OF MAIN-INLET BYPASS TO SUPPLY EJECTOR EXHAUST NOZZLE AT SUPERSONIC SPEEDS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An analysis has been made to evaluate the effectiveness of supplying secondary airflow for an ejector exhaust nozzle by bypassing from the main inlet. If close to optimum weight flow is maintained, the performance of such a system is about the same as for ejectors supplied by fixed auxiliary inlets up to at least a Mach number of 3.0.

In addition, up to a Mach number of 2.0 sufficient flow may be bypassed to ejectors to achieve optimum inlet-engine matching of fixed inlets and present-day turbojet engines. Engine net thrust is comparable to an inlet bypassing air to the free stream with the ejector supplied by a fixed auxiliary inlet. However, significant penalties may result if excessively large bypass amounts (as may be required for matching of higher Mach number designs) are put through ejectors rather than efficient auxiliary exits.

INTRODUCTION

It has been shown that ejector exhaust nozzles provide efficient operation over a wide flight range. The use of such nozzles requires a source of the secondary airflow. Auxiliary inlets mounted on the airframe which may serve this purpose are discussed in references 1 and 2. An alternate approach is to supply the ejector secondary air from the main inlet. For the latter arrangement, the external drag associated with the auxiliary inlet would be avoided, the secondary duct design would probably be simpler, and the availability of secondary air for engine cooling would be improved. There are a number of possible disadvantages, for example, ejector performance penalties due to the ingestion of free-stream rather than boundary-layer air (ref. 1), increased structural weight due to providing a duct from the main inlet to the ejector, and decreased airframe volume for storage.

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The use of a main-inlet bypass to the ejector may also be considered as a method for achieving off-design inlet-engine matching. For such an arrangement all flow delivered by the inlet at its most efficient operating point and not required by the engine would be bypassed around the engine to the ejector. Thus, the ejector pumping capacity would replace the usual type of variable inlet geometry (refs. 3 and 4). Of course, if it is found that less flow should be bypassed to the ejector than that required for efficient inlet-engine matching, variable inlet features may still be necessary.

This report examines analytically the use of the main engine inlet as the source of ejector secondary airflow and compares its performance to that of the auxiliary-inlet-supplied ejector up to a Mach number of 3.0. The use of ejectors for handling excess inlet flow not required by the engine is also considered. A performance comparison is made between this arrangement and the usual bypass-to-free-stream method of discharging excess inlet flows. In addition, an example is shown of the use of a bypass to the ejector for efficient matching of fixed inlets to present-day turbojet engines at Mach numbers up to 2.0.

SYMBOLS

A	area, sq ft
d	diameter, ft
$\frac{d_e}{d_p}$	ejector shroud exit diameter ratio $\frac{d_s}{d_p} = \frac{d_e}{d_p}$ for convergent ejectors
$\frac{d_s}{d_p}$	ejector shroud entrance diameter ratio
F	thrust
$\frac{F_{n,E} - \Delta D}{F_{n,p,i}}$	ratio of ejector net-thrust-minus-drag increment to ideal net thrust of primary jet
M	Mach number
m	mass flow, slugs/sec
$\frac{m_s}{m_0}$	spillage mass-flow ratio, ratio of flow captured by inlet that engine does not require to total flow captured by inlet

P	total pressure, lb/sq ft
$\frac{P_p}{p_0}$	primary nozzle pressure ratio
p	static pressure, lb/sq ft
T	total temperature, $^{\circ}R$
t	static temperature, $^{\circ}R$
w	weight flow, lb/sec
$\frac{w_s\sqrt{T_s}}{w_p\sqrt{T_p}}$	ejector corrected weight-flow ratio
$\frac{w\sqrt{\theta_1}}{\delta_1 A_1}$	engine corrected airflow, (lb/sec)/sq ft
δ	ratio of total pressure to NACA standard sea-level pressure of 2116 lb/sq ft
θ	ratio of total temperature to NACA standard sea-level temperature of 518.7° R

Subscripts:

d	duct
E	ejector
e	exit
eng	engine
i	ideal
n	net
p	primary
S	shroud
s	secondary, condition in duct at nozzle station
0	free stream
1	compressor face

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OPERATING CHARACTERISTICS

The type of system being considered is shown schematically in figure 1. This arrangement will be called herein the "inlet-bypass-to-ejector system." The secondary airflow for the ejector is obtained from the main inlet as shown in figure 1. Air enters the secondary duct through a subinlet, passes through the annular passage around the engine, and then enters the ejector exhaust nozzle. For some installations this flow could be passed through oil coolers, used for afterburner-shell cooling, or both.

When an ejector obtains its secondary airflow from any source, the operating point of the combination results wherever the ejector pumping characteristics match the supply system pressure-airflow characteristics (ref. 1). For a main-inlet bypass the supply characteristics will be a function of main-inlet pressure recovery, total-pressure losses entering the secondary duct, losses in the duct itself, and the size of the duct. The match point may be obtained as illustrated in figure 2 wherein the secondary pressure recovery P_s/P_0 is plotted against the ejector weight-flow parameter $w_s\sqrt{T_s}/w_p\sqrt{T_p}$.

The usual ejector pumping parameters P_s/P_p and $w_s\sqrt{T_s}/w_p\sqrt{T_p}$ may be converted to the form shown by

$$\frac{P_s}{P_0} = \frac{P_s}{P_p}\frac{P_p}{p_0}\frac{p_0}{P_0} \tag{1}$$

where P_p/p_0 (nozzle pressure ratio) and p_0/P_0 are functions of the free-stream Mach number.

The secondary pressure recovery P_s/P_0 may be obtained from the inlet pressure recovery P_1/P_0 by

$$\frac{P_s}{P_0} = \frac{P_1}{P_0}\frac{P_s}{P_1} \tag{2}$$

where P_s/P_1 is the loss across the secondary duct. This parameter was assumed equal to 0.95 for the examples given in this report. However, the trends were found to be the same in a limited check at a value of 0.70.

The operating line for the ejector-inlet combination shown in figure 2 would be along the line AC as long as the secondary duct size did not limit the flow. If the available secondary pressure recovery were lower than that assumed, the match points would shift lower but would still be on the ejector pumping characteristics. The duct size would limit the secondary flow if the flow became sonic anywhere in the duct. When the ejector tends to call for more flow than the duct will pass under this

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condition, the value of P_s/P_0 will fall because of shocks forming in the duct. The minimum flow area for duct choking may be obtained from

$$\frac{A_d}{A_1} = \frac{\left(\frac{w\sqrt{\theta}}{\delta_1 A_1}\right)_{eng}}{49.4} \frac{P_1}{P_d}\sqrt{\frac{T_p}{T_s}}\sqrt{\frac{T_d}{T_1}}\frac{w_s\sqrt{T_s}}{w_p\sqrt{T_p}} \tag{3}$$

Equation (3) may be used in selecting the subinlet and duct sizes which will allow the desired secondary flow to be passed through the duct over the entire flight plan. Generally, the flow through the duct would be subsonic except at the design condition when choking would occur.

When a predetermined ejector secondary flow is to be obtained from the main inlet, the effect upon inlet-engine matching must be evaluated. It can be shown that

$$\left(\frac{w\sqrt{\theta_1}}{\delta_1 A_1}\right)_{\substack{\text{Bypassed to}\\ \text{ejector}}} = \frac{w_s\sqrt{T_s}}{w_p\sqrt{T_p}}\left(\frac{w\sqrt{\theta_1}}{\delta_1 A_1}\right)_{eng}\sqrt{\frac{T_p}{t_0}}\sqrt{\frac{t_0}{T_0}}\sqrt{\frac{T_0}{T_s}} \tag{4}$$

On the other hand, the ejector may be used to handle excess inlet flow. Thus,

$$\frac{w_s\sqrt{T_s}}{w_p\sqrt{T_p}} = \frac{\frac{m_s}{m_0}}{1 - \frac{m_s}{m_0}}\sqrt{\frac{t_0}{T_p}}\sqrt{\frac{T_0}{t_0}}\sqrt{\frac{T_s}{T_0}} \tag{5}$$

If all the inlet flow not required by the engine at a desired inlet operating condition is bypassed around the engine

$$\frac{m_s}{m_0} = 1 - \frac{\left(\frac{w\sqrt{\theta}}{\delta_1 A_1}\right)_{eng}}{\left(\frac{w\sqrt{\theta}}{\delta_1 A_1}\right)_{\text{Inlet at optimum}}} \tag{6}$$

Substituting equation (6) into (5) yields

$$\frac{w_s\sqrt{T_s}}{w_p\sqrt{T_p}} = \left[\frac{\left(\frac{w\sqrt{\theta}}{\delta_1 A_1}\right)_{\text{Inlet at optimum}}}{\left(\frac{w\sqrt{\theta}}{\delta_1 A_1}\right)_{eng}} - 1\right]\sqrt{\frac{t_0}{T_p}}\sqrt{\frac{T_0}{t_0}}\sqrt{\frac{T_s}{T_0}} \tag{7}$$

from which the required ejector weight-flow ratio may be determined for any given inlet-engine combination.

DISCUSSION OF RESULTS

The performance of typical ejectors supplied by main inlets has been obtained from experimental ejector data (refs. 5 to 7) by means of assumed engine and inlet characteristics (fig. 3). Although the nozzle pressure ratio and inlet pressure recovery schedules may be different for a particular inlet-engine combination than that shown in figure 3, the results which follow are typical.

Figure 4 presents a performance comparison of three methods of supplying secondary weight flow to ejector exhaust nozzles. The basis of comparison is a thrust-minus-drag parameter $(F_{n,E} - \Delta D)/F_{n,p,i}$ wherein $F_{n,E}$ represents the net thrust of the ejector, ΔD any additional external drag caused by the particular configuration used to supply the secondary flow, and $F_{n,p,i}$ the ideal net thrust of the primary jet. The secondary flow was either obtained from auxiliary inlets (performance from refs. 1 and 2) or from the main inlet. Results for both variable and fixed auxiliary inlets are shown. For the main-inlet-supplied ejector the size of the inlet would necessarily be increased to supply both the engine and the ejector. The step in the curves shown here at a free-stream Mach number of 0.8 is due to operation with and without afterburning.

In order to obtain close to the variable-auxiliary-inlet performance with a fixed-auxiliary-inlet design, care has to be exercised in selecting the inlet size. Otherwise, either significant additive drag or thrust losses due to weight-flow reductions will result. Also, if the ejector flow were obtained from the main inlet, a reduction in the available secondary pressure would be required (above a free-stream Mach number of 2.1 for divergent ejectors and above a free-stream Mach number of 1.3 for convergent ejectors). Otherwise a much higher secondary flow than optimum would be pumped from the main inlet, resulting in significantly lower thrust. However, figure 4 indicates that if properly designed and close to optimum flow is obtained, ejectors may be supplied by either a main inlet or a fixed auxiliary inlet and provide performance close to that of a variable-auxiliary-inlet system.

In figure 4 consideration was only given to the main inlet as a source of ejector secondary flow which was controlled to be close to the optimum value. If the inlet-bypass-to-ejector system is considered as a means of discharging inlet flow in excess of engine requirements, the ejector may be called upon to operate at values of $w_s\sqrt{T_s}/w_p\sqrt{T_p}$ that are not close to optimum (eq. (7)). In figures 5 and 6, the inlet-bypass-to-ejector

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system for handling excess inlet flow is compared to an external bypass system (i.e., the usual bypass arrangement). In the latter case, the ejector was considered to be supplied by a fixed auxiliary inlet. For this comparison, the ΔD term in the thrust parameter is equal to the auxiliary-inlet drag (ref. 2) plus the spillage drag of the auxiliary exit (momentum difference of the excess flow computed from one-dimensional relations). For the inlet-bypass-to-ejector system ΔD is equal to zero. Thus, figures 5 and 6 compare the drag increase associated with the usual bypass system to the thrust penalties associated with the inlet-bypass-to-ejector system for ejectors having realistic shroud exit diameter ratios. These thrust reductions result from either changes in ejector geometry to handle the flow (for divergent ejectors) or operation at other than optimum secondary ejector flow (for convergent ejectors, see ref. 1).

The spillage drag of the usual bypass system has been computed by assuming an auxiliary exit discharging the flow axially into the free stream. Any effect on external drag of either the auxiliary exit itself or the jet from this exit has not been included. The spillage drag thus computed may be low. As indicated in reference 8, an auxiliary exit which is discharging flow from a body at an angle to the external flow may suffer from low thrust ratios (i.e., ratio of actual to theoretical jet thrust). If the exit were placed in the axial direction to overcome this thrust loss, an increase in the external drag may result. In either eventuality, the performance of the bypass-to-free-stream system would be lower than that shown in figures 5 and 6, thus improving the relative position of the inlet-bypass-to-ejector system.

The performance with divergent-shroud ejectors is shown in figure 5. As pointed out in reference 5 such ejectors are desirable above a Mach number of about 1.6 to achieve peak thrusts. Since the thrust performance of the divergent ejectors increases with decreasing shroud entrance diameter, the shroud entrance diameter ratio d_S/d_p should be selected to be as close to 1 as possible and still handle the required flow. The optimum ejector expansion ratio d_e/d_p is set by the nozzle pressure ratio and, for this type ejector, does not influence the ejector pumping ability.

The performances of the two techniques for bypassing excess inlet flow are competitive up to a bypass amount which varies with free-stream Mach number. As Mach number increases, the spillage drag for the usual bypass arrangement increases rapidly such that the inlet-bypass-to-ejector system appears better up to higher bypass amounts. The drop in performance at all Mach numbers of the inlet-bypass-to-ejector system with high secondary flows is due to the large increase of the shroud entrance diameter required for the ejector to handle the bypass flow.

A performance comparison with two convergent ejectors at a Mach number of 2.0 is shown in figure 6. The poorer performance at the high secondary flows of the inlet-bypass-to-ejector system when used with convergent shroud ejectors is due to the inability of convergent ejectors to develop as much jet thrust at high secondary flow as can be obtained from an auxiliary exit handling the same flow. The comparisons shown in figures 5 and 6 are, of course, subject to the assumptions stated previously. If the flow from the auxiliary exit were not as efficient as assumed, the inlet-bypass-to-ejector system would be much more competitive.

An example of the use of the inlet-bypass-to-ejector system for matching a specific inlet and engine over a Mach number range is next considered. 5000 Two engines having different slopes of their airflow curves and a fixed inlet were assumed (fig. 7). If an engine-bypass arrangement is to be used, the inlet would ordinarily be sized for the low Mach number (in this example, 0.8) and the compression surface positioned for the oblique shock on lip at the high Mach number. Thus, the inlet, if operated critically, would supply more flow than the engine would require above a Mach number of 0.8. To prevent subcritical inlet operation, this excess flow may be passed through either the ejector or an auxiliary exit. Equations (6) and (7) were utilized in determining the bypass amounts required to match the inlet and engines of figure 7.

If the inlet-bypass-to-ejector system were used, the ejector weight-flow and geometry requirements to maintain critical inlet operation would be as shown in figure 8. When supplying the ejector as well as the engine, it is desirable to oversize the inlet slightly so that some secondary flow would always be available to the ejector. For the example considered, the inlet was sized so that at a free-stream Mach number of 0.8, the ejector secondary weight-flow ratio $w_s\sqrt{T_s}/w_p\sqrt{T_p}$ was 0.03. From figure 8(a) it can be seen that not only does the amount of flow to be handled by the ejector increase with free-stream Mach number, but in addition, this flow increases rapidly as the engines' airflows become more sensitive to flight Mach number (fig. 7(a)). For example, at a Mach number of 2.0 operation with engine B would require the ejector to handle four times as much secondary air as with engine A.

Comparison of the bypass weight-flow requirements and the available pressure recovery with ejector pumping characteristics (refs. 5 to 7) yields the ejector geometry required (fig. 8(b)). It was assumed that the ejector shroud would be sufficiently long to have little effect on the pumping ability of the ejector. The values presented in figure 8(b) represent the minimum diameter ratio to handle the required airflow. Since ejectors having larger diameter ratios would pump the same flow but at a lower secondary pressure recovery, such ejectors would require a throttle in the secondary passage. The diameter ratios shown are for divergent shroud ejectors and represent the shroud entrance diameter. However, these curves would be modified only slightly for ejectors having convergent shrouds. For the latter case, the diameter ratio shown refers to the shroud exit diameter.

Since the desired diameter ratio varies with free-stream Mach number, it is apparent that operation with a fixed ejector requires an oversized diameter ratio with a variable throttle in the secondary passage. For such a case, the ejector diameter ratio selected is the maximum required over the flight path. If the ejector diameter ratio were less than that required, not enough inlet flow could be bypassed and the inlet would be forced to operate subcritically. With the diameter ratio greater than that required, the inlet would operate supercritically, unless the secondary pressure recovery were reduced by throttling.

The ejector geometry for efficient inlet-engine matching may be selected in a number of ways. If the shroud were convergent (good thrust up to a free-stream Mach number of about 1.6 and not extremely sensitive to off-design operation), the shroud diameter ratio d_s/d_p may be as follows:

(1) Variable and equal to optimum (fig. 8(b)). The maximum thrust for convergent ejectors would result. A throttle in the secondary duct would be required, however, since this ejector would tend to pump too much flow from the main inlet over the entire flight plan.

(2) Variable and equal to that required to handle the necessary flow (fig. 8(b)). No throttle necessary but thrust lower than that for case (1).

(3) Fixed either at or greater than the largest diameter ratio required over the flight path. Provisions for secondary pressure throttling would be necessary, and the ejector would suffer from the relatively slight off-design thrust losses associated with convergent shrouded ejectors.

If the shroud were divergent (generally best ejector geometry for a free-stream Mach number greater than 1.6 (ref. 5)), the shroud diameter ratios may be selected as follows:

(1) The shroud exit variable and set at the optimum for each Mach number; the entrance diameter variable and equal to that required to pump enough flow to maintain critical inlet operation. No additional throttling would be necessary and the best possible performance obtainable with a divergent ejector would result.

(2) The shroud exit variable and set at the optimum for each Mach number; the entrance fixed at the maximum required to handle the necessary flow (e.g., at a free-stream Mach number of 2.0 (fig. 8(b))). Secondary-flow throttling would be necessary and slightly poorer thrust than that of case (1) would result.

(3) Shroud exit and entrance both fixed. Secondary throttling would be necessary, and the ejector would suffer from the large off-design thrust losses (ref. 5) associated with divergent ejectors.

The choice of shroud type and its variation is, obviously, a compromise between performance and mechanical complexity. However, to illustrate the performance of an ejector configuration which handles the necessary flow to match a fixed inlet and engine properly, a divergent shroud ejector with a fixed entrance diameter and a variable exit diameter has been assumed (fig. 9). In one case a variable-area bypass discharging to the free stream is used to match the inlet and engine, and a fixed auxiliary inlet is used to supply the ejector. For the other case the excess inlet flow is ducted to the ejector, that is, the inlet-bypass-to-ejector system. In the latter case a secondary throttle is used to control the bypass airflow. The performance of the two systems is comparable when used with engine A. However, since operation with engine B requires large secondary flows, the usual external bypass - auxiliary inlet system appears superior. The large bypass flows required necessitated large shroud entrance diameter ratios for the inlet-bypass-to-ejector system resulting in lower thrust. As noted previously, this comparison would obviously be altered if the auxiliary exit drag and thrust ratio were poorer than was assumed.

Since the ejector considered in figure 9 was of the fixed-diameter-ratio type, control of the secondary-flow pressure would be required to match the inlet and engine properly. At a free-stream Mach number below 2.0, for this example, the total pressure of the secondary flow at the nozzle station must be reduced or the inlet would be forced to operate supercritically. The amount of total-pressure reduction is shown in figure 10. As can be seen, the necessary reduction is quite large in the intermediate Mach number range and a variable throttle would probably be required. As with any variable inlet feature, the throttle setting should be controlled by the inlet operating point to ensure proper operation. It would appear that inlet controls similar to those discussed in reference 9 might be employed.

SUMMARY OF RESULTS

The following results were obtained from an analysis to a free-stream Mach number of 3.0 of ejectors for which the secondary air was supplied by the engine inlet.

1. If the secondary flow is controlled such that close to optimum weight flow is established, the thrust performance of ejectors supplied by the main inlet is comparable to ejectors supplied by variable auxiliary inlets.

2. Significantly lower thrust will result when an excessive amount of inlet flow is bypassed to ejectors rather than discharged from axial auxiliary exits.

3. Applicability of using bypass-to-ejector systems for proper matching of engines to fixed inlets is dependent on the engine airflow characteristics. The greater the variation of engine airflow with Mach number, the poorer the performance as compared to the usual inlet bypass arrangement.

4. Generally when an ejector is supplied its secondary flow by a main inlet, a throttle in the secondary duct would be required.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 9, 1956

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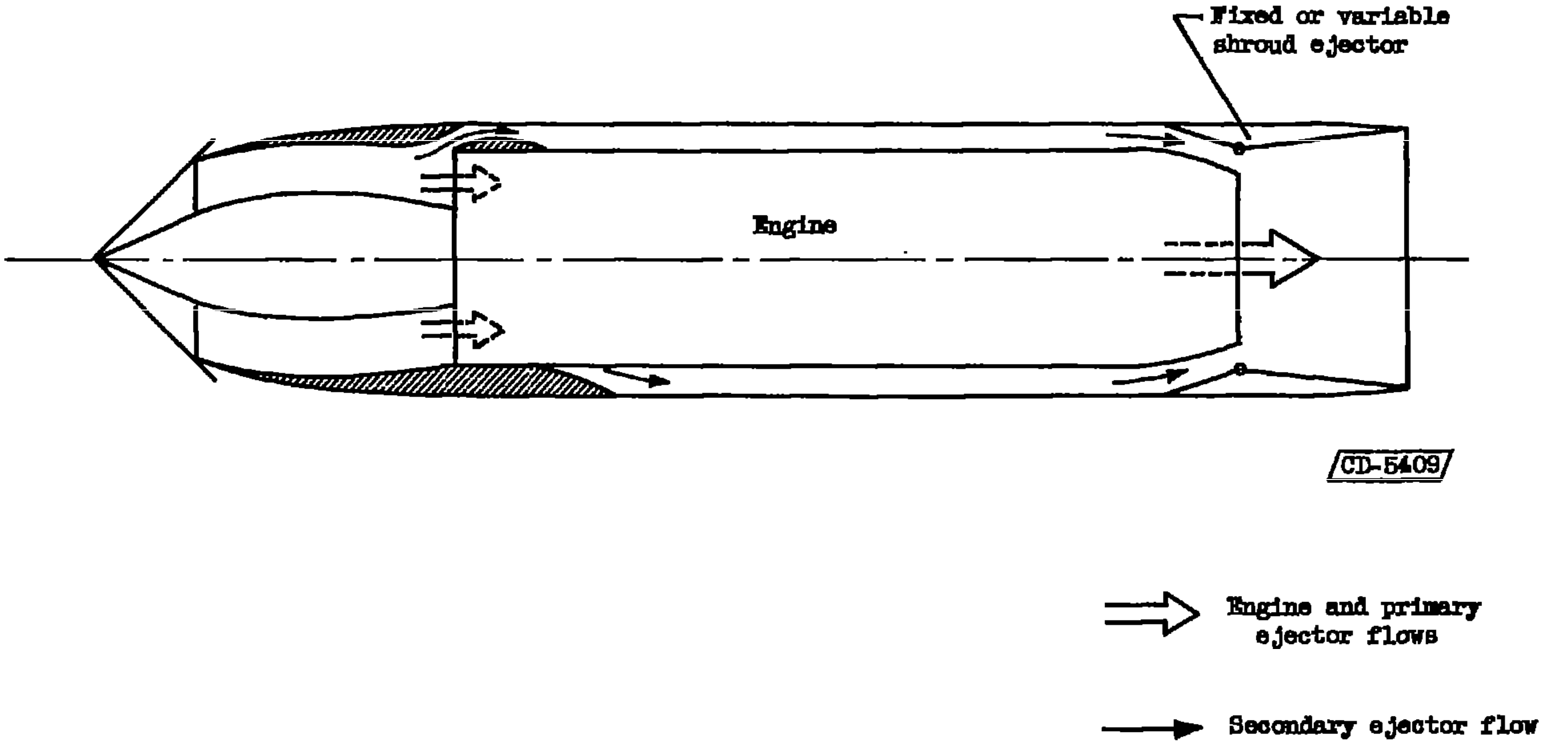

Figure 1. - Inlet-bypass-to-ejector system.

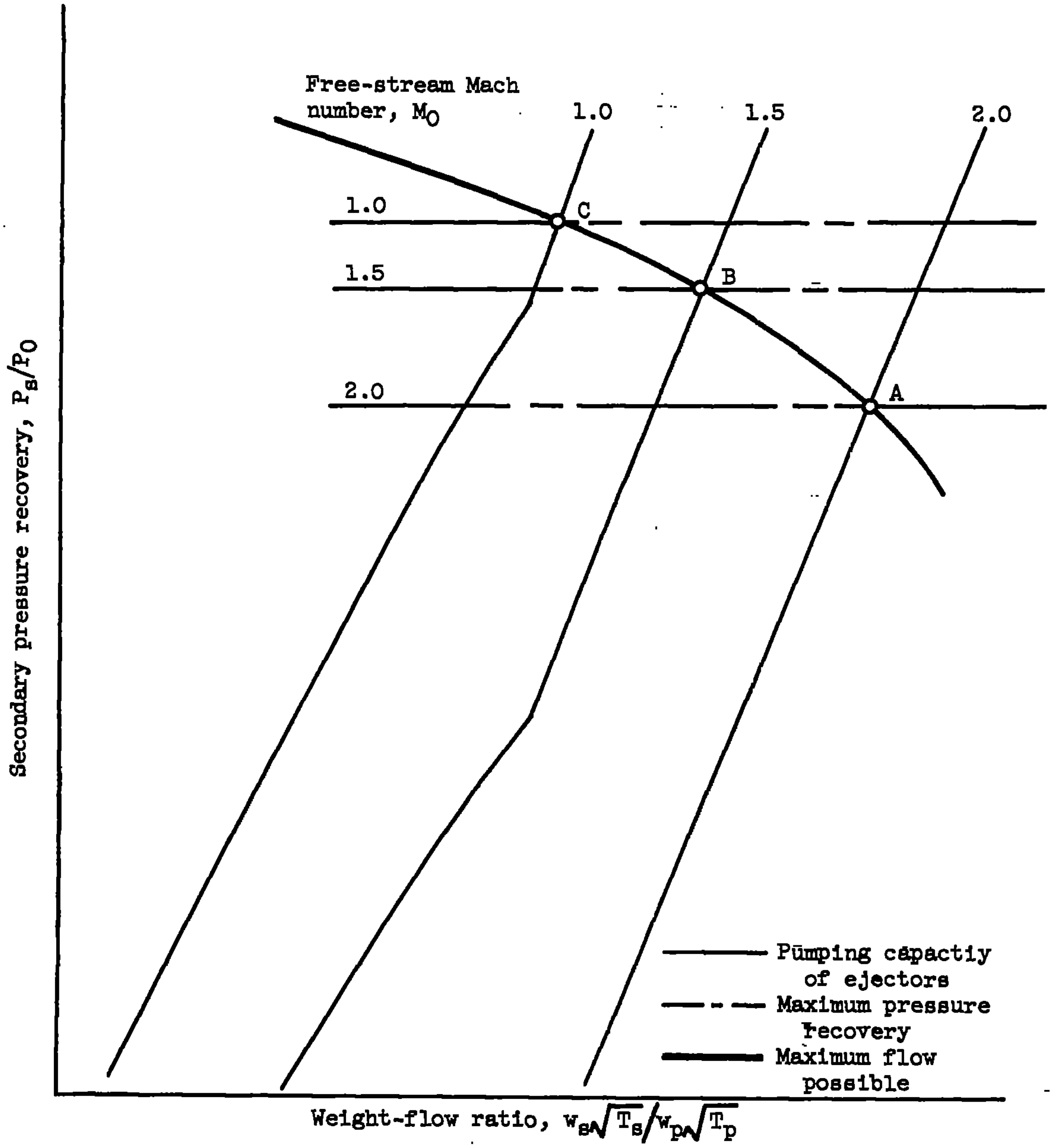

Figure 2. - Matching of ejector pumping characteristics to duct pressure recovery.

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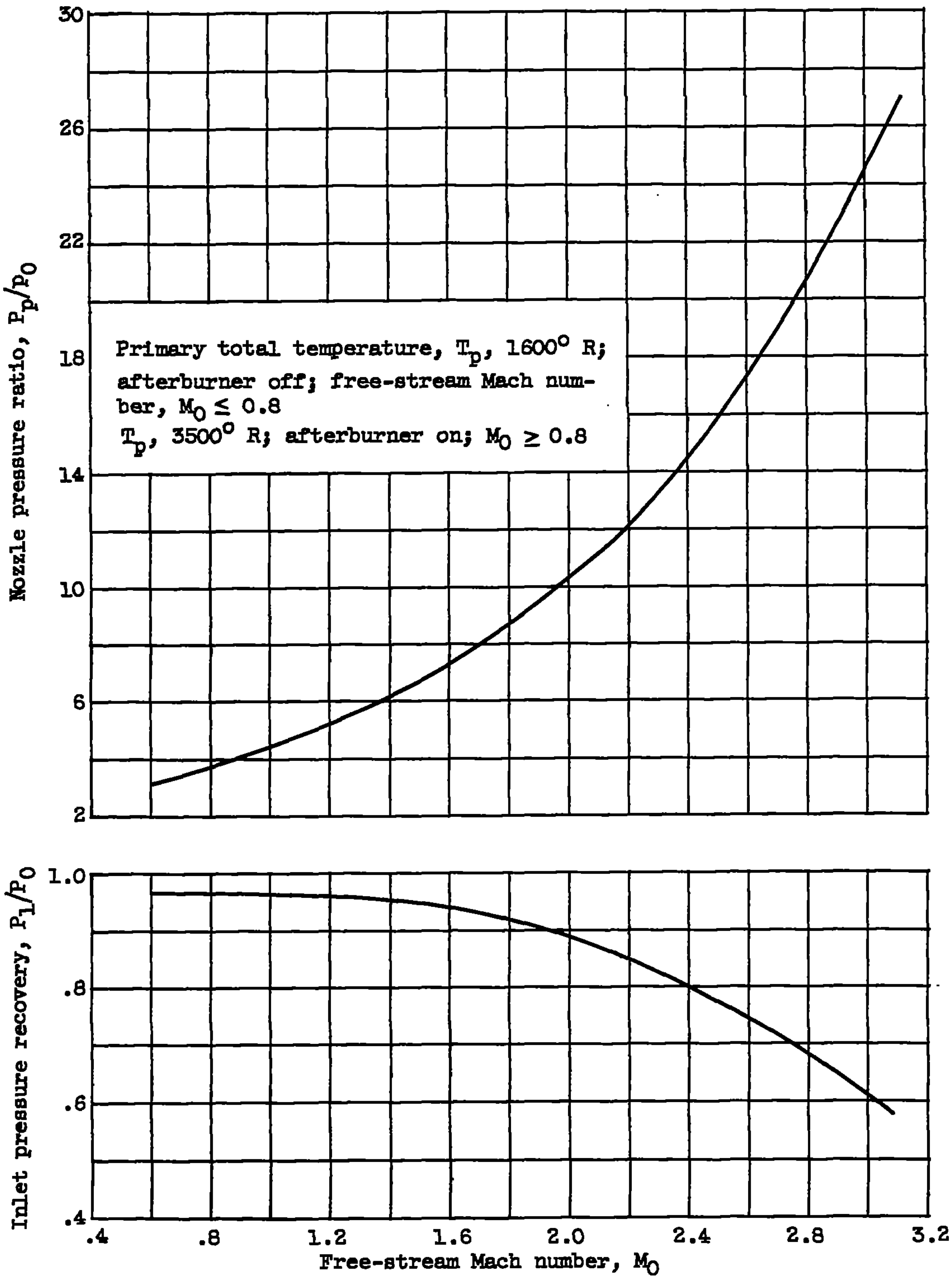
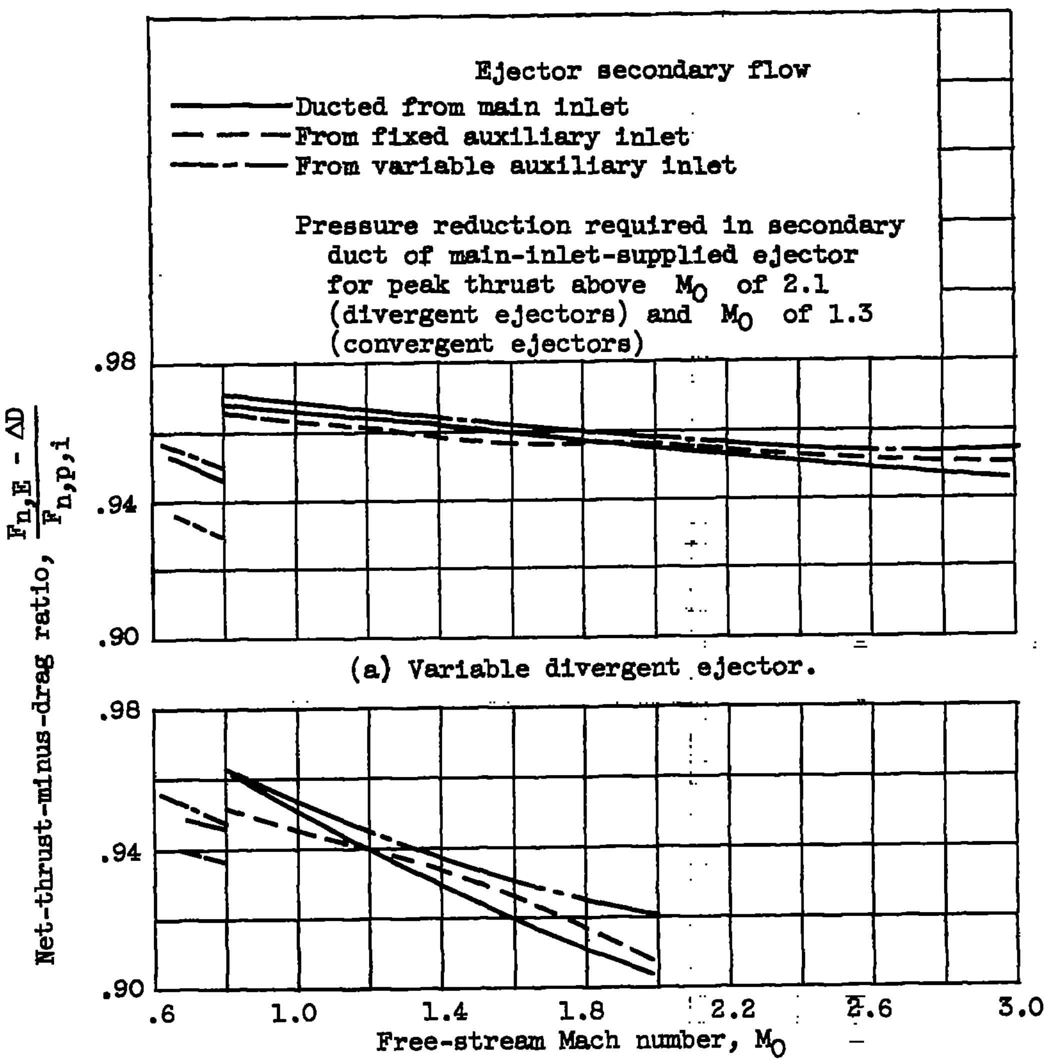


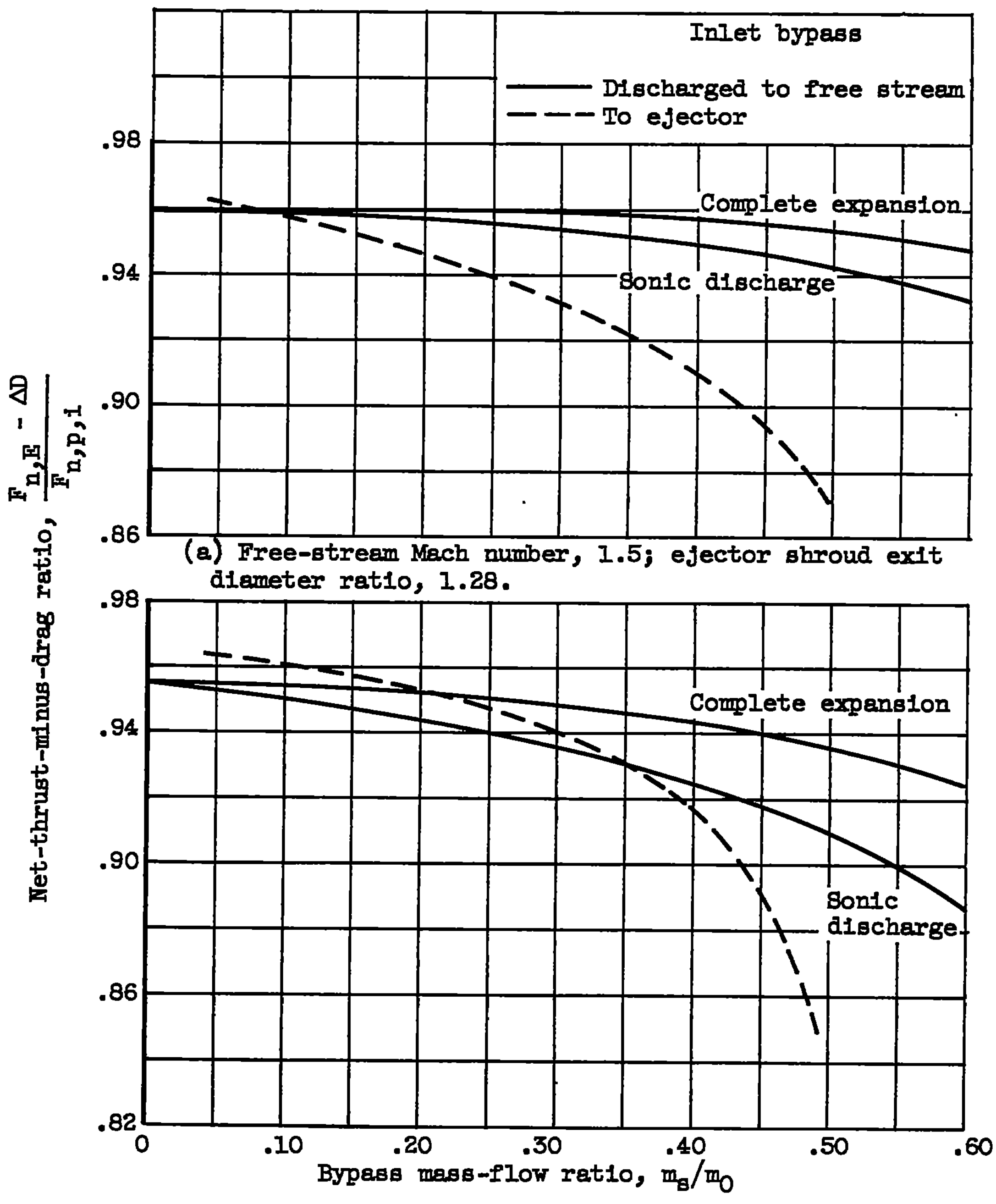
Figure 3. - Assumed engine pressure ratio and inlet pressure recovery schedules.



(a) Variable divergent ejector.

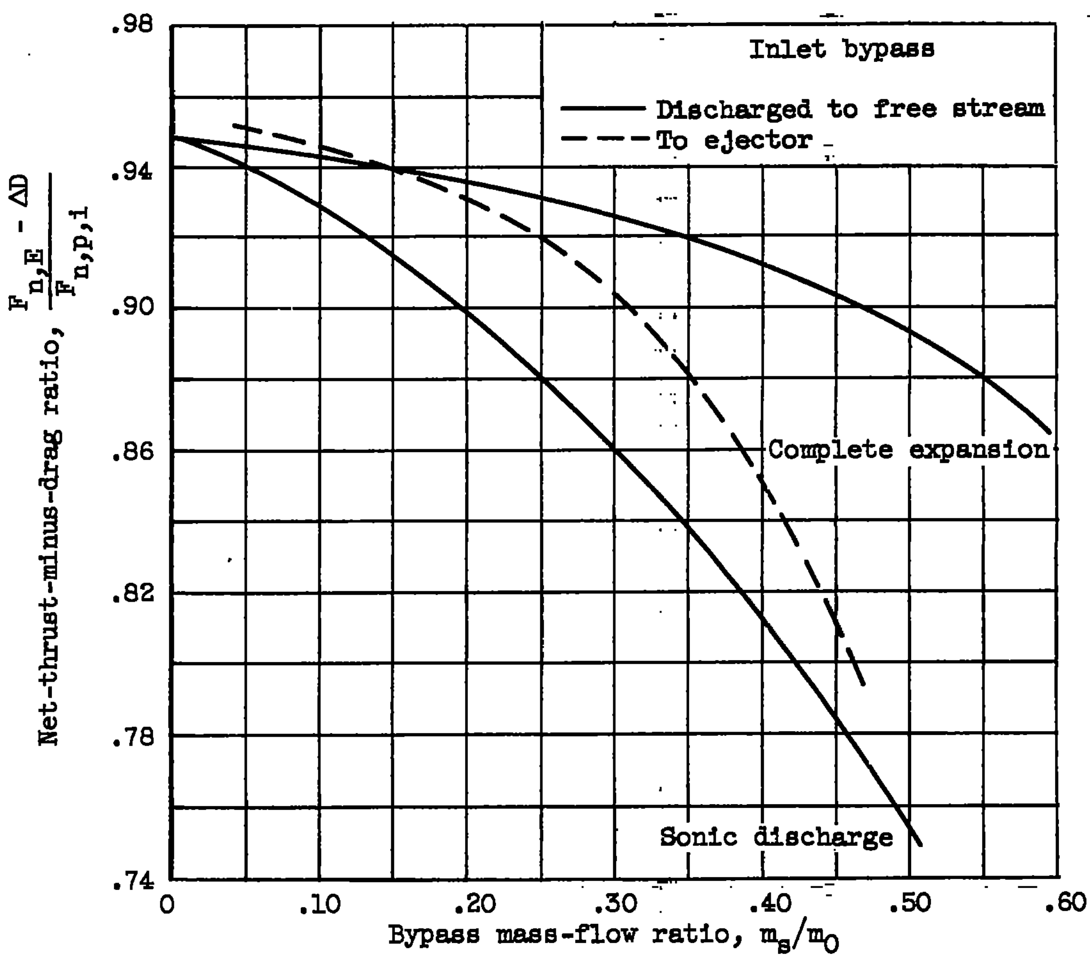
(b) Variable convergent ejector.

Figure 4. - On-design performance comparison of engine main-inlet- and auxiliary-inlet-supplied ejectors.



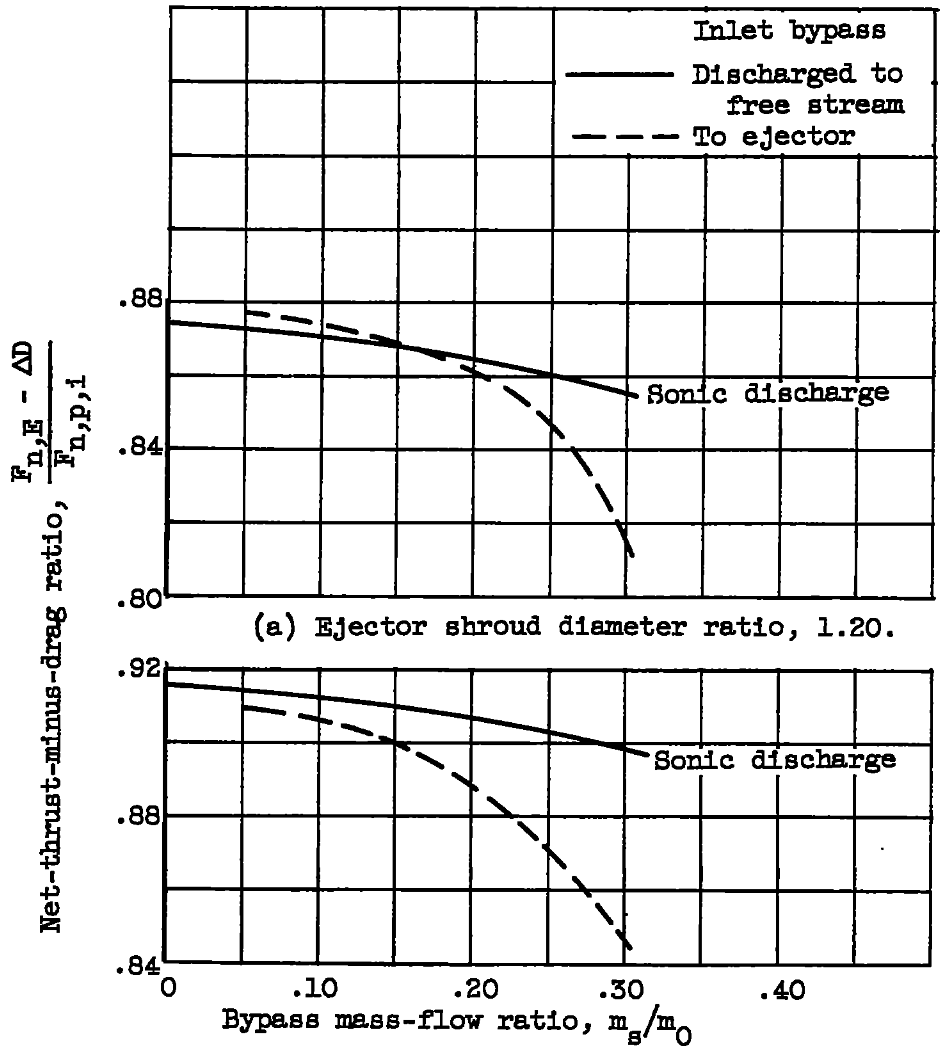
(b) Free-stream Mach number, 2.0; ejector shroud exit diameter ratio, 1.45.

Figure 5. - Performance comparison of bypassing excess main-inlet flow through auxiliary exits and to divergent ejectors.



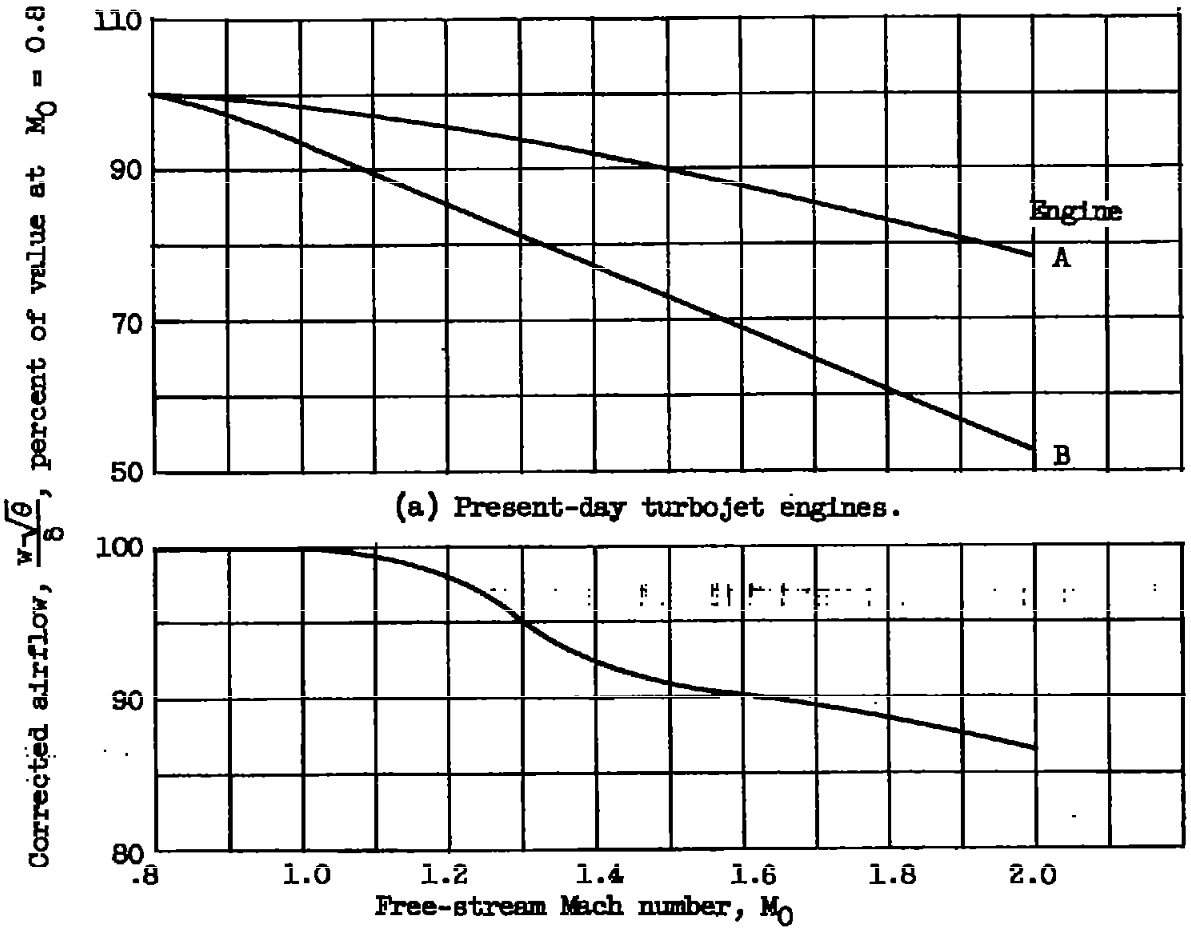
(c) Free-stream Mach number, 3.0; ejector shroud exit diameter ratio, 1.82.

Figure 5. - Concluded. Performance comparison of bypassing excess main-inlet flow through auxiliary exits and to divergent ejectors.



(b) Ejector shroud diameter ratio, 1.40.

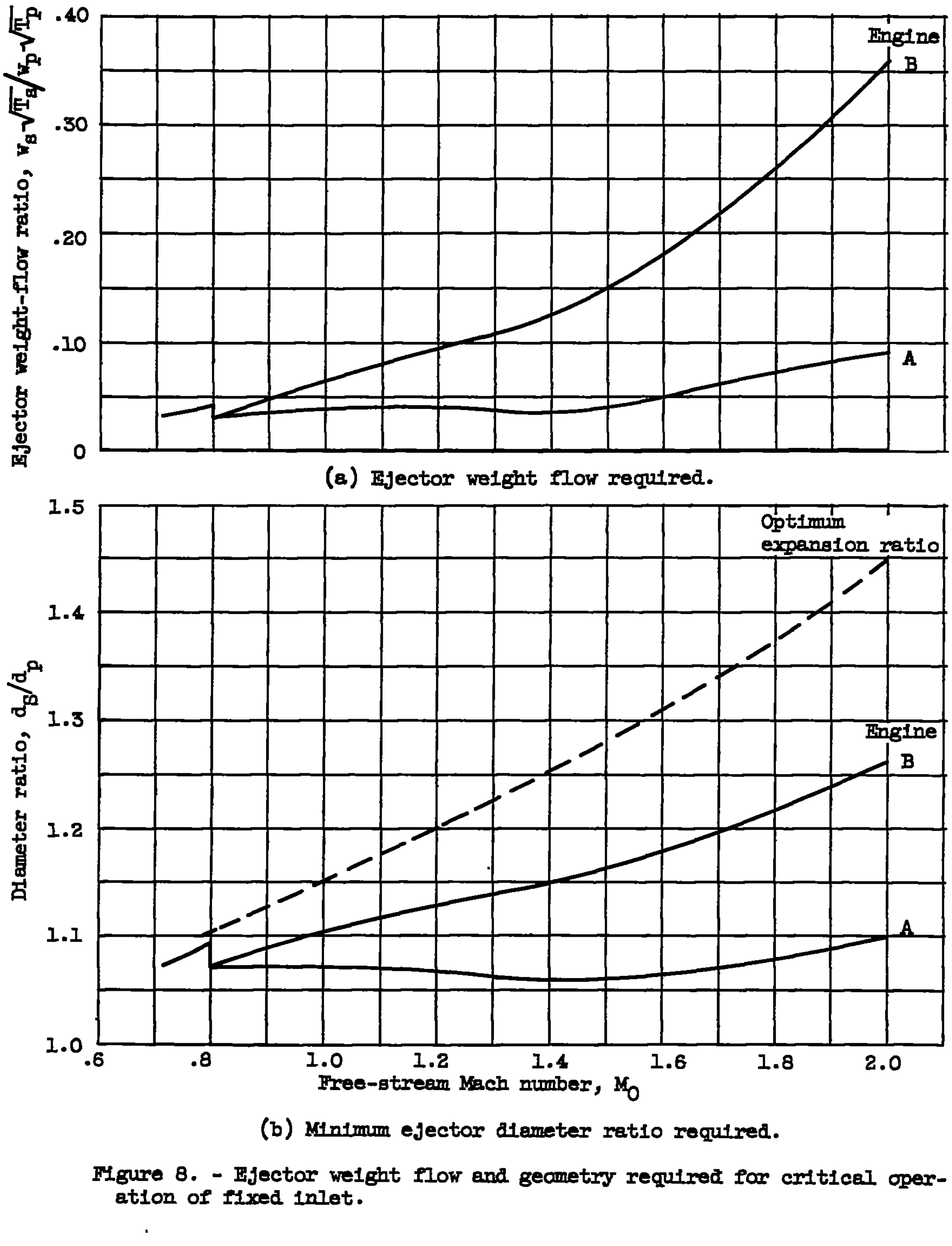
Figure 6. - Performance comparison of bypassing excess main-inlet flow through auxiliary exits and to convergent ejectors. Free-stream Mach number, 2.0.



(a) Present-day turbojet engines.

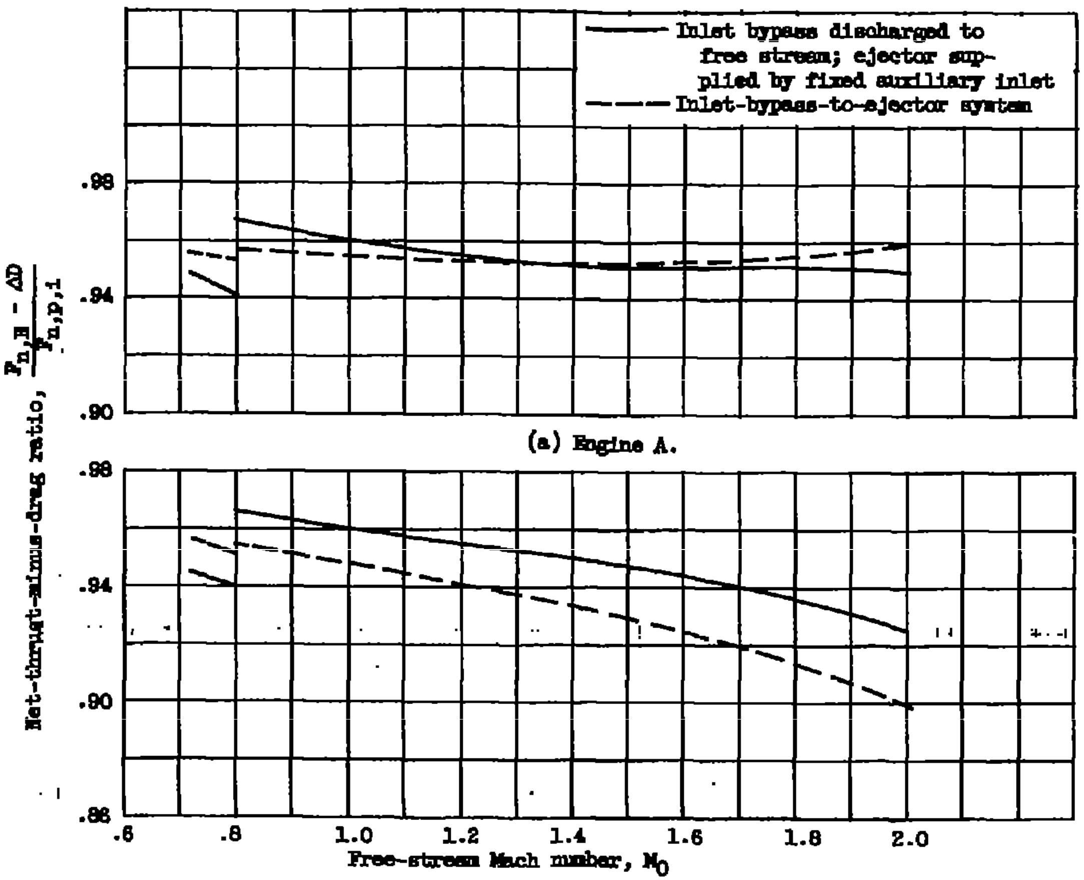
(b) Fixed 25° half-angle cone inlet.

Figure 7. - Assumed engine and fixed inlet airflow characteristics.



(b) Minimum ejector diameter ratio required.

Figure 8. - Ejector weight flow and geometry required for critical operation of fixed inlet.



(a) Engine A.

(b) Engine B.

Figure 9. - Performance comparison with divergent ejector up to free-stream Mach number of 2.0 of critical inlet operation achieved by bypassing to ejector and by discharging through auxiliary exit.

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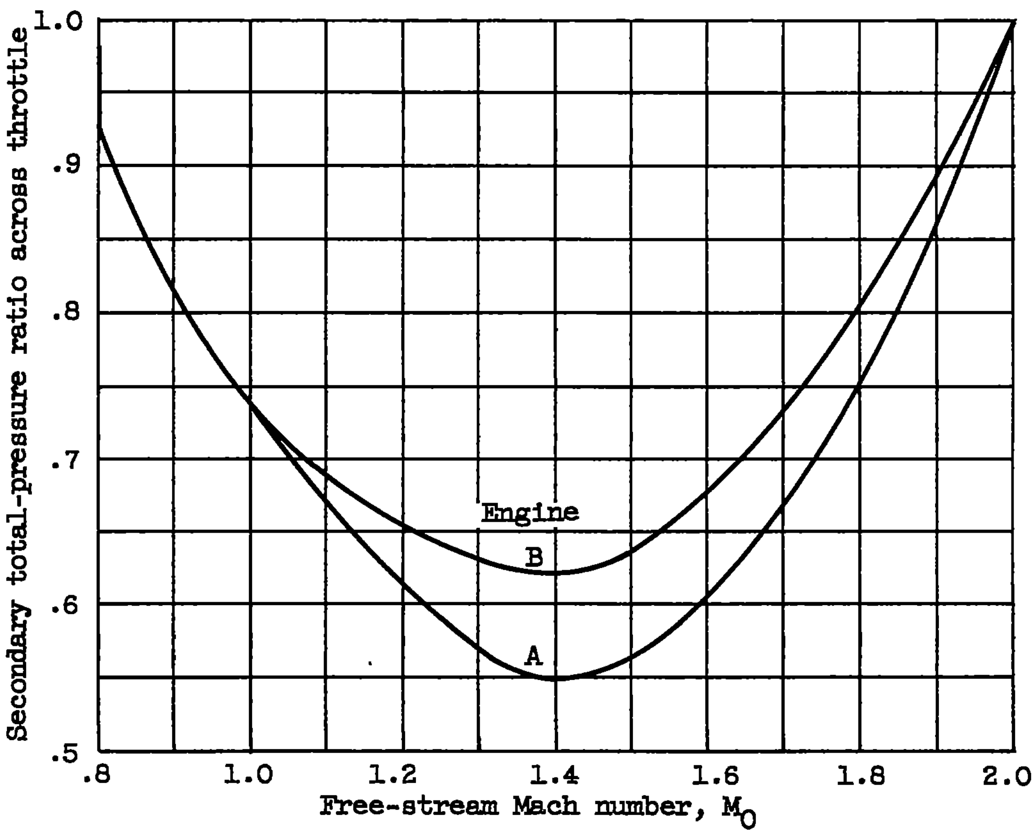

Figure 10. - Pressure reduction required of secondary flow to maintain critical inlet operation if diameter ratio is fixed.